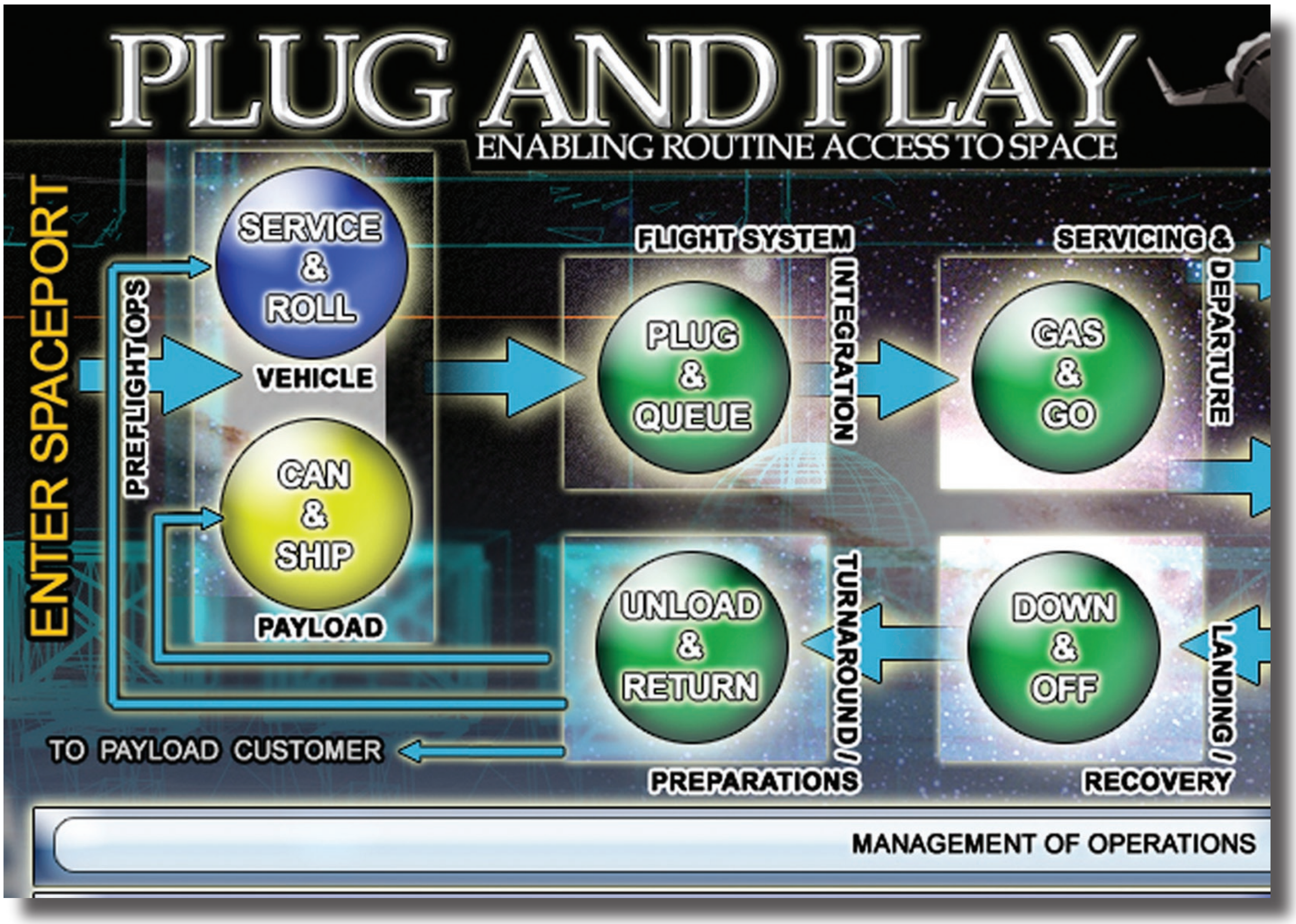


Figure 17. Plug & Play vision of spaceport operations

4 What is the vision for ideal spaceport operations?

Standardized facility and hardware interfaces that simplify vehicle and payload processing without significant reconfiguration between flights. "Plug & Play," a visionary operations model, provides a conceptual environment to develop and integrate these objectives.

Today the ideal spaceport is defined in a vision, but tomorrow spaceports will become vital hubs ushering in a revolution in transportation. The number of spaceports will increase as space transportation becomes affordable, and spaceports will handle a growing variety of vehicles. Plug & Play, as shown in Figure 17, depicts the ideal condition where a variety of vehicle architectures or payload customers can seamlessly integrate into the spaceport operations. Extensive reconfiguration of hardware and/or infrastructure is not required to accommodate different vehicle or payload designs. It is envisioned that the spaceport will integrate a vehicle or payload in much the same way a computer recognizes new hardware attached to it and installs the drivers necessary to use it.

The intent of the Plug & Play model is to simplify and standardize interfaces between the spaceport and the flight hardware without compromising the flight hardware performance. Significant cost and schedule savings can be realized with standardization because it eliminates the need for reconfiguration between missions.

4.1 How did Plug & Play evolve?

The concept was developed by examining individual subfunctions and identifying ways to improve them.

The Plug & Play vision is a synthesis of contemporary spacecraft processing and commercial airport operations. Elements of the preflight and postflight ground operations were examined for both existing spaceflight vehicles and airport operations in an effort to identify common themes or ideals. Figure 18 and Table 2 depict the relationships of the individual subfunctions of the generic spaceport operations model shown in Figure 13 to the Plug & Play model.

Reducing ground operations timelines has always been an objective with any space access program. In March 2002, Kennedy Space Center (KSC) was tasked by the NASA Space Launch Initiative (SLI) program to answer two intertwined questions:

- **Why does it cost so much to operate the Space Shuttle?**
- **Why does it take so long to process the Shuttle?**

In response, KSC initiated a root cause analysis (RCA) study to analyze the problem. The RCA study collected as-run data from the Space Shuttle program relating to clock hours required to perform the relevant tasks for turnaround operations for a mission. The mission analyzed was Atlantis STS-81 in early 1997 when the Space Shuttle program was operating at its best launch capacity of 7 to 8 flights per year. This was a typical mission and not one that followed a major overhaul maintenance period of several months.

Figure 19 illustrates the distribution of Shuttle processing clock hours per spaceport subfunction identified in the generic spaceport operations model (Figure 13). The total processing time for STS-81 was estimated at 42,000 clock hours, including planned and unplanned tasks. The most time-consuming spaceport subfunctions were:

- **B1: Assemble Flight Elements**
- **C1: Service Flight Elements**
- **I1: Restore Flight Elements**

Servicing the Orbiter during the stand-alone operations in the Orbiter Processing Facility (e.g., C1: Service and Checkout Flight Elements) consumed 23.7 percent of the overall clock hours required for the entire mission processing. This subfunction is very time-consuming because of the sheer number of systems that must be tested to verify their flight worthiness prior to each mission. The time required for mission preparations must be reduced if airportlike operations are to ever become a reality.

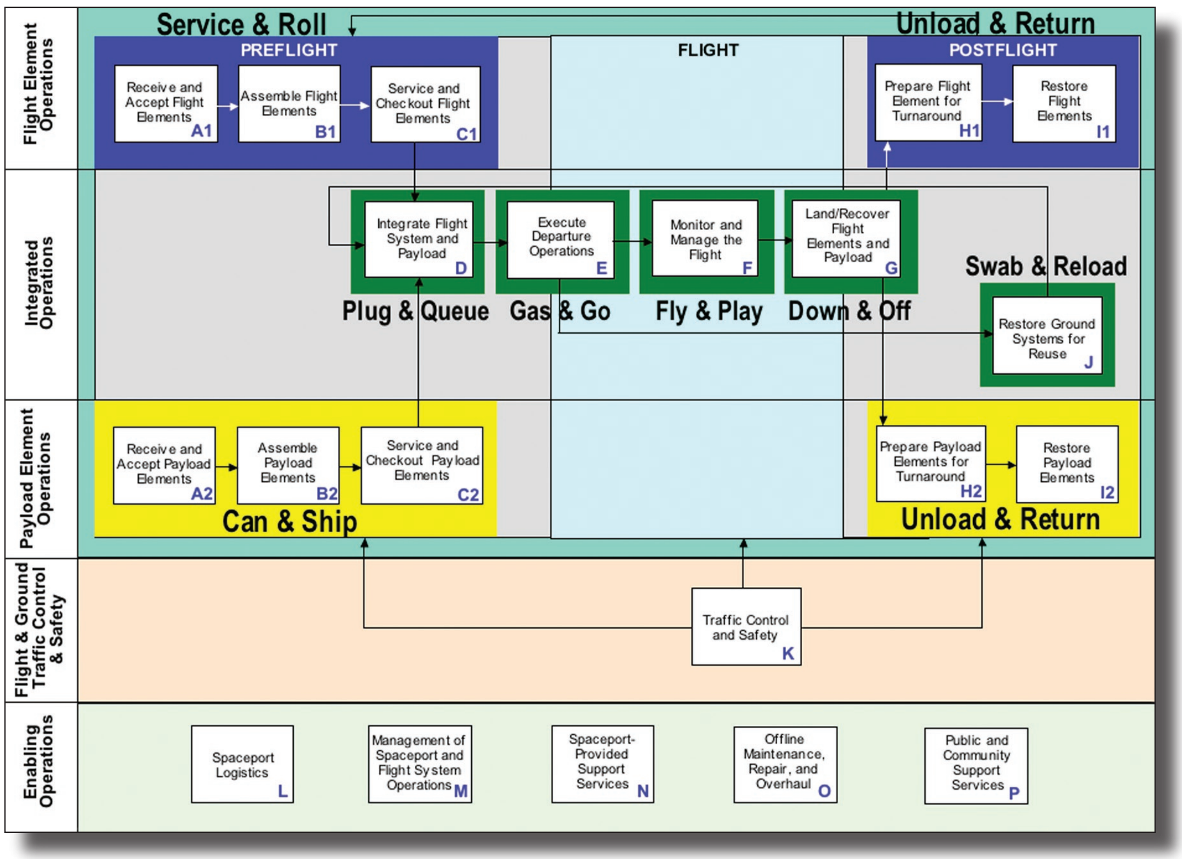


Figure 18. Plug & Play mapped to the generic spaceport operations model

Table 2. Mapping the generic spaceport operations model to the Plug & Play model

Phase	Ideal Characteristics	Subfunctions (*)
Flight Element Preflight Operations	**Service & Roll** Minimal servicing and/or routine, scheduled turnaround that replenishes consumables only and performs a power-up diagnostics test to quickly reveal faults and anomalies without user interaction.	Receive and Accept Flight Elements (A1)
		Assemble Flight Elements (B1)
		Service and Checkout Flight Elements (C1)
Payload Preflight Operations	**Can & Ship** "Containerized" payload that is self-sufficient (does not rely on vehicle for its resources) and has standard interfaces for integration to the flight vehicle.	Payload Element Receipt and Acceptance (A2)
		Assemble Payload Elements (B2)
		Service and Checkout Payload Elements (C2)
Integrated Operations	**Plug & Queue** Simple and standard interfaces that allow for self-aligning surfaces and autonomous and rapid integration of payload and flight vehicle.	Integrate Flight System and Payload (D) (Vehicle Perspective)
		Integrate Flight System and Payload (D) (Payload Perspective)
	Gas & Go On-demand propellant servicing to the flight vehicle and/or payload and quick verification that vehicle is ready to fly.	Execute Departure Operations (E) (Vehicle Perspective)
Flight Operations	**Fly & Play** Flexible and responsive departure control and range support.	Monitor, Control, and Manage the Flight (F) (Vehicle Perspective)
Postflight Operations	**Down & Off** Routine landing with self-safing systems and rapid removal from runway. Shortly after wheel stop, the vehicle is immediately (minutes) transported to the next processing location.	Land/Recover Flight Elements and Payload (G)
	Unload & Return (Flight Element) Informed maintenance where status of vehicle is communicated to spaceport via power-up diagnostics test to quickly reveal faults and anomalies without user interaction.	Prepare Flight Elements for Turnaround or Disposal (H1)
		Restore Flight Elements (I1)
	Unload & Return (Payload Element) Rapid disconnect of modularized payload and rapid transfer to customer.	Prepare Payload Elements for Turnaround or Disposal (H2)
		Refurbish Payload Elements (I2)
		Refurbish Payload Elements (I2)
Postflight Refurbishment	**Swab & Reload** Robust spaceport ground systems with informed maintenance where status of systems is communicated via power-up diagnostics test that quickly reveal faults and anomalies. Repairs and resets are remotely or autonomously performed without direct user interaction.	Restore/Reservice Ground Systems for Reuse (J)

* Letters in parentheses refer to the subfunction identifier. Refer to *Spaceport Subfunctions Definitions* in Appendix D.

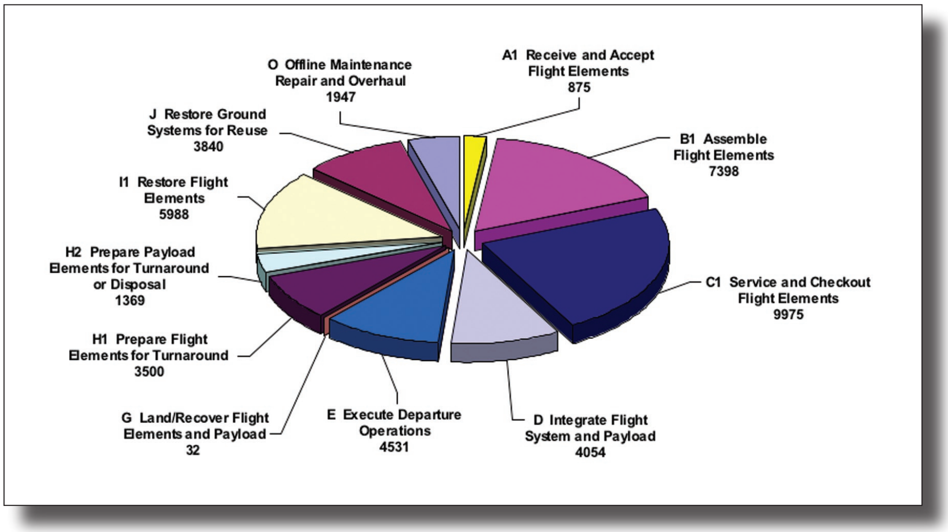


Figure 19. STS-81 work content by ASTWG subfunction – sum of task duration (clock hours)

This Space Shuttle data helps focus the efforts of identifying key areas to improve total processing time. The overall goal is to reduce the total clock hours required to process a spaceflight vehicle by addressing some of the time-intensive subfunctions performed to ready the vehicle for its mission. The ideal time line for each subfunction of the Plug & Play model is charted in Figure 20.

In the near term, the goal is to reduce processing times from approximately 42,000 clock hours down to 1,600 clock hours, with the ultimate goal of less than 100 clock hours per mission. This can only be accomplished by infusing advanced technologies into the vehicle as well as into the spaceport systems to ensure that the ground support equipment has a high availability.

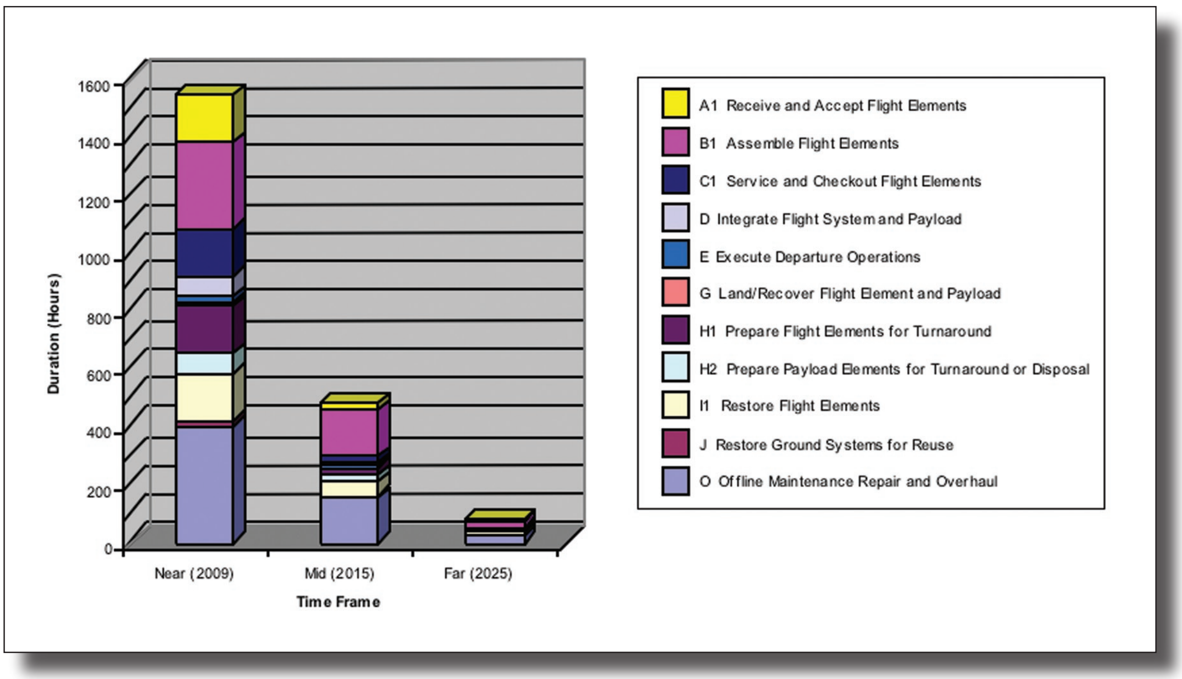


Figure 20. Plug & Play model ideal timelines (near-, mid-, and far-term goals

4.2 How is Plug & Play constructed and how does it work?

Plug & Play divides the overall spaceflight vehicle ground operations process into six phases:

- ***Flight Element Preflight Operations***
- ***Payload Preflight Operations***
- ***Integrated Operations***
- ***Flight Operations***
- ***Postflight Operations***
- ***Postflight Refurbishment***

and examines each phase from four analytical perspectives to identify its components and improve its processes.

Key Characteristics

A summary description of the key characteristics and/or subfunctions associated with the Plug & Play phase.

Concept of Operations

How the spaceport customer would experience the phase. The concept of operations provides a story of the ideal conditions during that phase of the operation. A summary capability roadmap is included to show the evolution of the desired capabilities moving toward the ideal state.

Challenges

Discussion of some of the key hurdles associated with the current operations and potential technology barriers to achieving the ideal concept of operations.

Technical Approaches

Some of the potential approaches to overcoming the challenges and hurdles.

Figure 21 illustrates the process phases and the analytical perspectives of the Plug & Play model. The following subsections provide only a summary of the work accomplished in defining the ideal characteristics, challenges, and technical approaches. For further details, please refer to Appendices D through I.

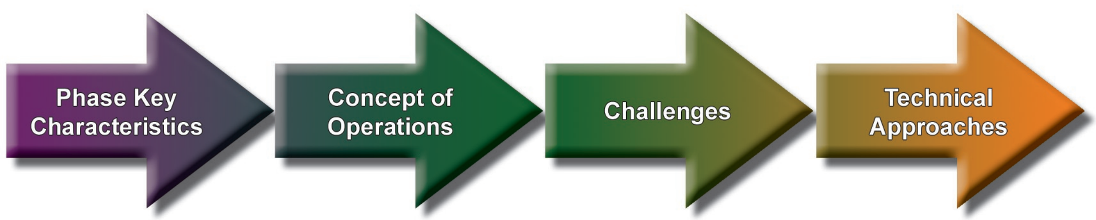
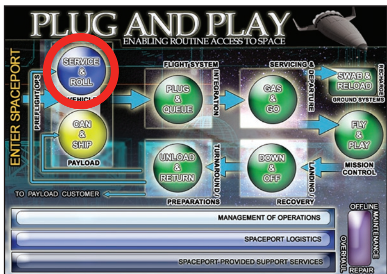


Figure 21. Structure of Plug & Play model

4.2.1 Flight Element Preflight Operations – *Service & Roll*



Minimal servicing and/or routine, scheduled turnaround that replenishes consumables only and performs a power-up diagnostics test to quickly reveal faults and anomalies without user interaction.

Key Characteristics

- **Minimal servicing of the flight element**
- **Self-diagnostics with autonomous repair**

Concept of Operations

The Service & Roll phase employs a minimal servicing philosophy. The initial flight of a vehicle element will require some inspection and assembly at the spaceport. The flight element will have advanced diagnostics that can immediately detect any technical problem the hardware might experience during transport to and through the spaceport so the problem can be remedied upon arrival. Assembly and servicing of any subsystems will be minimal because system interfaces will be simple and standardized. Initial checkout of the flight element will employ built-in diagnostics capability with self-fault isolation and repair.

All subsequent flights for reusable vehicles will model the current airline industry with a focus on the basic philosophy of quick turnaround. Automated service checkouts will identify problems early, reducing maintenance time to levels similar to or better than today's commercial airliners. A service check might include verifying that all systems are functional and ready to perform, as well as readying the cargo bay for the payload – cargo or passengers. The vehicle is now ready to roll to the next phase of the operation.

The evolution of capabilities required to perform the Service & Roll functions is summarized in Figure 22. A more detailed description of the capability evolution can be found in Appendix E.

Challenges

The Service & Roll concept is a radical paradigm shift from current-day reusable launch vehicle processing. Today in the Shuttle program, after each mission, many of the vehicle subsystems are disassembled for inspection and system checkout for the next flight. This operating philosophy requires specialized support equipment because each system is unique. The spaceport is then burdened with maintaining this specialized equipment with activities such as ensuring the calibration is within specification and the proof load is current. Standardization of ground support equipment is one method of streamlining operations for Service & Roll.

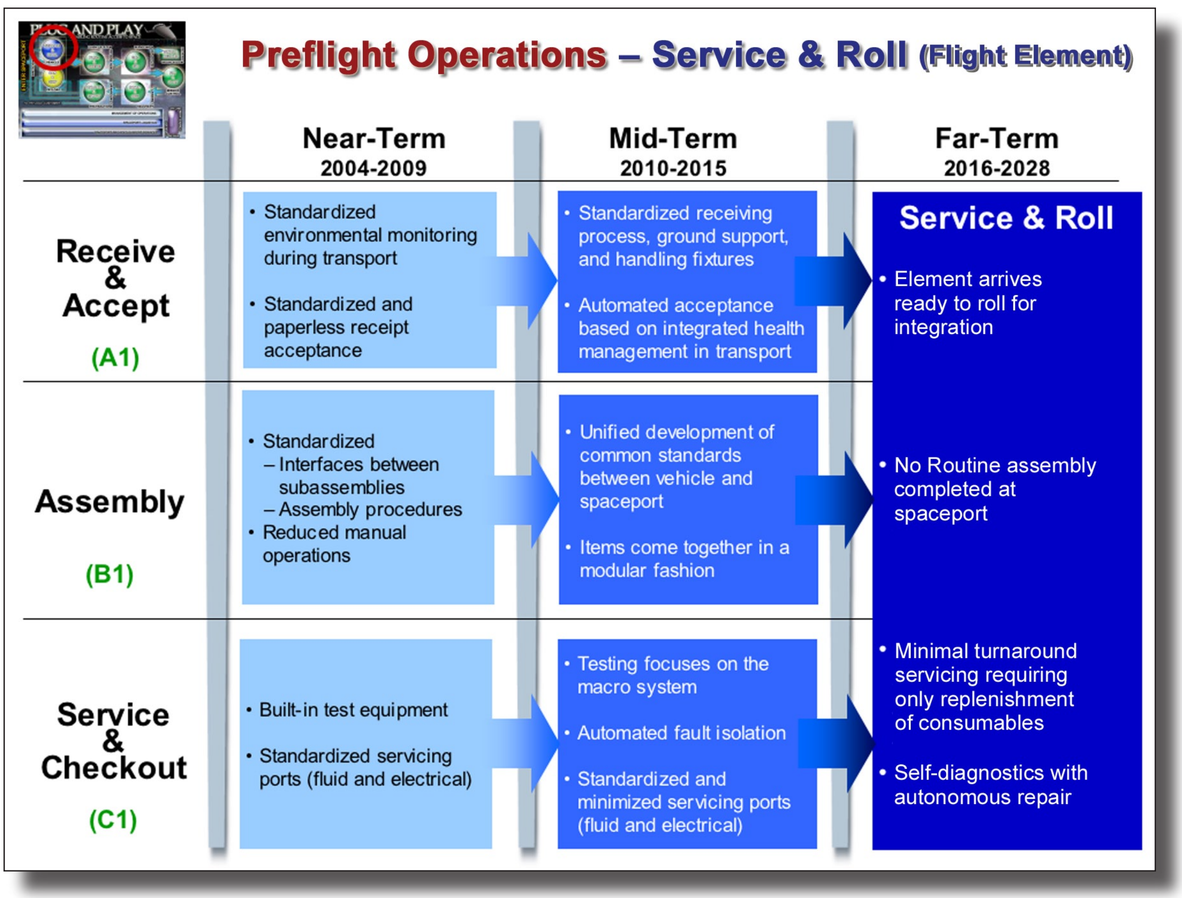


Figure 22. Service & Roll functional capabilities roadmap summary

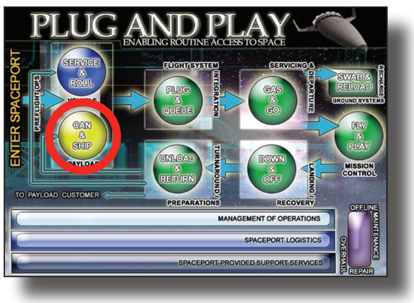
Technical Approaches

The need for standardization is prevalent throughout the spaceport concept of operations. The standardization of interfaces among vehicle systems, ground systems, and intercomponent connections spans mechanical, electrical, fluid, and data systems. Nonintrusive, nondestructive evaluation techniques can also help turn the vehicle around faster since they eliminate disassembly of the system for inspections. And finally, implementing integrated health management of all support equipment allows for predictive or condition-based maintenance, ensuring high availability of the support equipment when needed. Table 3 summarizes the challenges and key technologies associated with the Service & Roll concept. A more detailed description of the challenges and technical approaches can be found in Appendix I.

Table 3. Key challenges and technologies for Service & Roll

Challenges	Spaceport Technologies
• Unique interfaces create the need for specialized/unique support equipment • Handling of multiple and hazardous propellants is dangerous and requires extensive leak detection • Sensing, understanding, and testing the health of the ground systems is complex, redundant, and intrusive	• Advanced planning and scheduling tools – Dynamic scheduling – Situational awareness – Human-machine interfaces – Intelligent software agents • Standard interfaces between ground systems and flight hardware • Self-sealing, self-cleaning ground support equipment quick disconnects • Advanced materials for ground support equipment – Lightweight, high-strength composites – Smart materials • Integrated health management for ground systems – Neural networks – Artificial intelligence – Adaptive algorithms – Data fusion techniques – Self-diagnostic/remediation techniques • Advanced sensors – Micro-Electromechanical Systems (MEMS) – Nanotechnology • Nonintrusive nondestructive evaluation techniques – Laser imaging – Robotic inspections • Leakproof connectors and seals • Low-maintenance insulation systems (e.g., for cryogenics) • Inexpensive, nonintrusive hazardous gas and leak detection systems • Latching technologies (e.g., pneumatic bushings) • Commodities production and recovery and disposal management systems • Advanced corrosion mitigation techniques for ground support equipment

4.2.2 Payload Element Preflight Operations – *Can & Ship*



"Containerized" payload that does not rely on the vehicle for its resources and has standard interfaces for integration to the flight vehicle.

Key Characteristics

- **Self-sufficient containerized payloads**
- **Standard interfaces**
- **Automated calibration and self-fault identification**
- **Minimal payload servicing**

Concept of Operations

The Can & Ship phase of the Plug & Play model requires that payloads arrive at the spaceport processing areas ready to fly or needing only minimal prelaunch preparation. The payload can be as simple as computer equipment, as critical as medical supplies, or as advanced as a weather forecasting satellite. The Can & Ship phase includes the encapsulation/preparation of articles, equipment, specimen, and experiments for integration into the flight vehicle. This phase also serves as the initial point of quality verification for subsystem testing and carrier inspections and the validation of payload interfaces in a stand-alone configuration.

The Can & Ship function ultimately presumes payloads elements, experiments, specimens, and articles will evolve into self-contained modules. Interfaces between the spacecraft and payload delivery system will be minimized and standardized. This concept is modeled upon the current air parcel shipment industry. The concept reflects the basic philosophies of containerization and minimal physical interfaces, which preclude integrated testing requirements and resource loading of vehicle systems.

The evolution of capabilities required to perform the Can & Ship functions are summarized in Figure 23. A more detailed description of the capability evolution can be found in Appendix F.

Challenges

There are a number of challenges associated with achieving the Can & Ship vision. Currently, payload processing at the spaceport lacks standard approaches to inspection, handling, testing, and servicing. The payload arrives at the spaceport in piece-parts generally requiring significant assembly. These challenges must be overcome so the Can & Ship philosophy can be applied to ground operations at the spaceport.

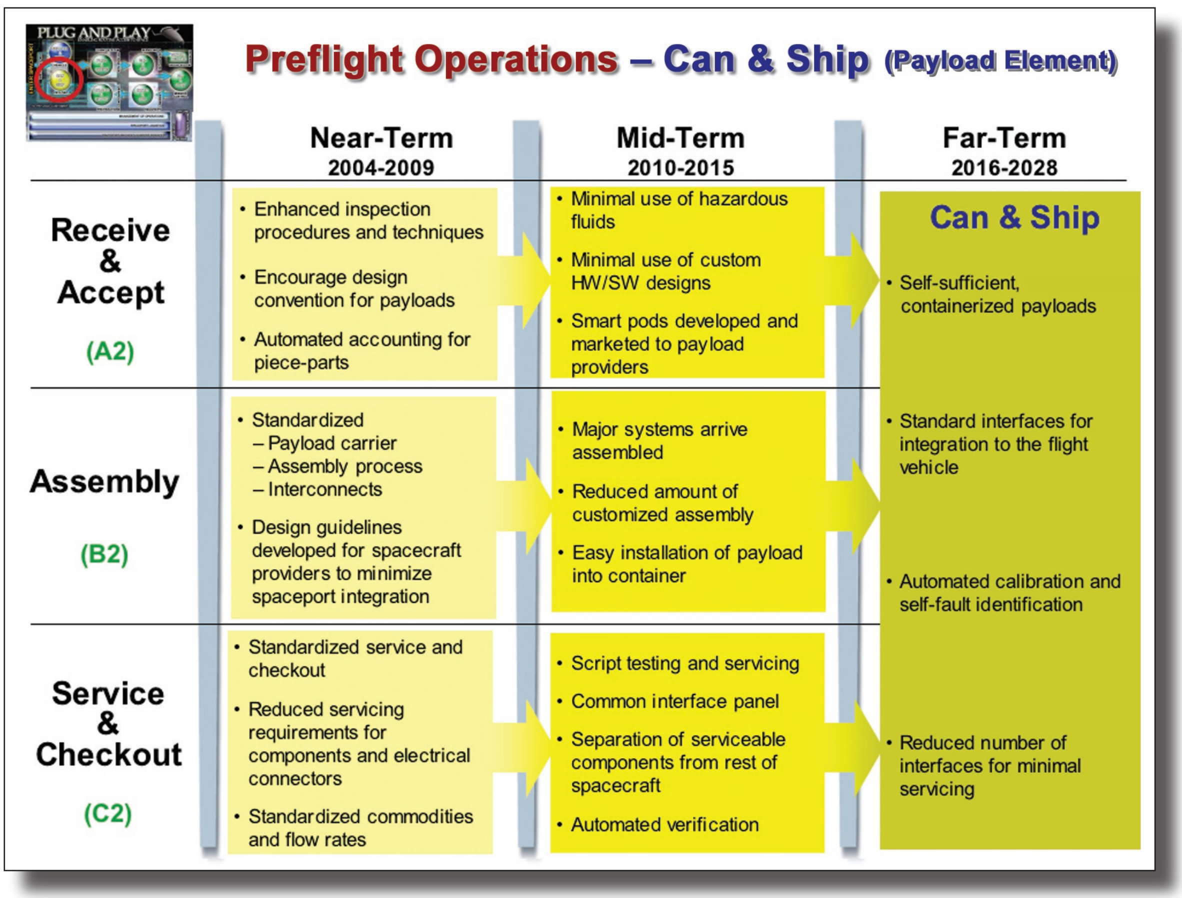


Figure 23. Payload Can & Ship functional capabilities roadmap summary

Technical Approaches

Technical capabilities required to efficiently satisfy this phase of the vision include those associated with artificial intelligence in the arena of inspections/self-fault annunciation. In addition, standardizing interfaces for both hardware and software, minimizing servicing requirements for payload systems and controls, and improved containerization techniques and systems are critical to the success of the operation. Table 4 summarized the key technologies to enable the Can & Ship phase. A more detailed description of the challenges and technical approaches can be found in Appendix I.

Table 4. Key challenges and technologies for Can & Ship

Challenges	Spaceport Technologies
• Lack of standard payload approaches creates unique requirements for – Inspection – Handling – Testing – Servicing • Handling hazardous commodities is dangerous • Nonstandard containers and connectors lead to specialized handling/testing equipment • Sensing, understanding, and testing payload health is iterative and incremental	• Advanced payload ground transporter • Standard payload transport canister • Advanced payload containerization techniques – Automated verification techniques • Standard interfaces for ground support equipment • Integrated health management for payload – Neural networks – Artificial intelligence – Adaptive algorithms – Data fusion techniques – Self-diagnostic/remediation techniques • Advanced sensors – MEMS – Nanotechnology • Nonintrusive nondestructive evaluation techniques – Laser imaging – Robotic inspections • Advanced materials for ground support equipment – Lightweight, high-strength composites • Smart materials

4.2.3 Integration of Flight Element and Payload Element – *Plug & Queue*

Simple and standard interfaces that allow for autonomous and rapid integration using common lift points, self-aligning surfaces, autonomous umbilicals, and self-fault isolation and repair techniques.

Key Characteristics

- **Automated integration**
- **Self-verifying interfaces**
- **Self-fault isolation and repair**
- **Autonomous hardware recognition and reconfiguration**

Concept of Operations

The Plug & Queue phase provides an environment that consists of systems designed to readily accommodate the integration of various types of flight and payload elements. Operations feature physical integration using highly automated, mechanically enhanced systems and techniques; and intelligent systems capable of self-diagnosis/remediation. For example, robotic capabilities with artificial intelligence will perform the element integration operations. Self-alignment and verification interfaces will assist and expedite the integration process by eliminating the need for human spotters. Once all elements are integrated into a complete system, the ground checkout system will autonomously reconfigure based on the recognition of the flight hardware to be tested.

The evolution of capabilities required to perform the Plug & Queue functions is summarized in Figure 24. A more detailed description of the capability evolution can be found in Appendix G.

Challenges

One of the major challenges to the Plug & Queue concept is the assembly of the flight elements into an integrated vehicle. Flight hardware operations today are slow because of the complex positioning, rotating, and lowering of the flight elements. These operations require highly skilled crane operators who can perform intricate maneuvers in both speed and position. In addition to the crane operators, numerous human spotters are required to verify proper clearance between the flight hardware and any obstruction to avoid collateral damage during assembly operations. Final assembly and closeout of the interfaces also tends to be very labor-intensive, requiring special craftsmanlike skills because of the uniqueness and complexity of the interfaces.

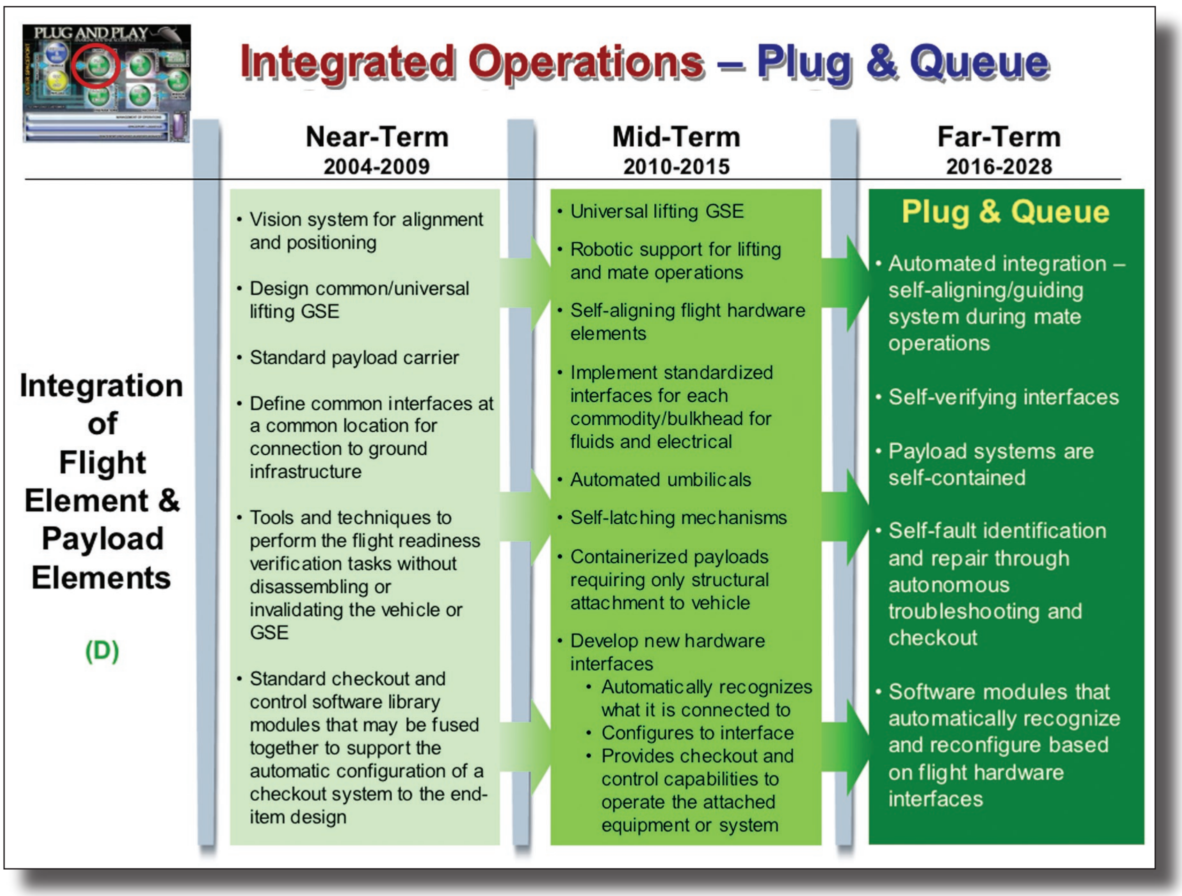


Figure 24. Plug & Queue functional capabilities roadmap summary

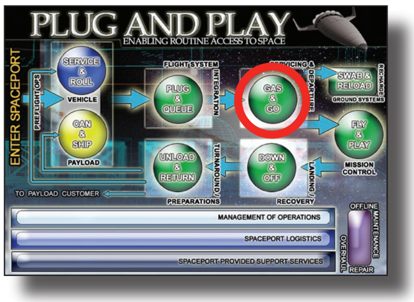
Technical Approaches

An examination of the Plug & Queue subfunctions reveals an environment rich in opportunities for efficiencies and technological enhancement. Technological capabilities that can help overcome these challenges, including advanced alignment and position sensors, artificial intelligence, and autonomous command and control capabilities, will enable the Plug & Queue phase. Key technologies associated with Plug & Queue are shown Table 5. A more detailed description of the challenges and technical approaches can be found in Appendix I.

Table 5. Key challenges and technologies for Plug & Queue

Challenges	Spaceport Technologies
• Intricate positioning, rotation, and handling of flight elements is difficult, time-consuming, and requires specialized equipment • Interface verification, testing, and checkout is manual • Handling and installation of pyrotechnic separation systems is dangerous and time-consuming • Complex, nonstandard interfaces lead to increased labor for connection and inspection • Mission/vehicle-unique checkout and control systems create multiple systems	• Advanced planning and scheduling tools – Dynamic scheduling – Situational awareness – Human-machine interfaces – Intelligent software agents • Precision physical control technologies • Robotic handling systems • Nonpyrotechnic, debrisless separation techniques • Standard Interfaces – Self-verifying connections – Self-latching mechanisms • Integrated health management for payload and spaceflight vehicle – Neural networks – Artificial intelligence – Adaptive algorithms – Data fusion techniques – Self-diagnostic/remediation techniques • Advanced alignment, mate, and release mechanisms (e.g., advanced optical alignment technologies)

4.2.4 Execution of Departure Operations – *Gas & Go*



On-demand fluid servicing of the flight vehicle and/or payload and quick verification that vehicle is ready to fly.

Key Characteristics

- **Clean pad/runway**
- **On-demand propellant system**
- **Autonomous umbilical extend and retract**
- **Onboard control of preflight operations**
- **Skeleton crew for departure operations**

Concept of Operations

The execution of departure functions, or the Gas & Go phase, encompasses the tasks associated with final fueling operations, embarkation of passengers and crew, synchronization with ground controllers, final craft checkout and configuration for launch activities, and other operations that prepare for the commencement of flight operations. It is envisioned in the Plug & Play model that the departure point will be universal such that any vehicle architecture can be accommodated. The departure point, whether it is a launch pad or a runway, will have minimal interfaces to the vehicle or payload.

Fueling the vehicle and servicing the payload (if necessary) will be rapid in the future, not the hours-long process currently required for space vehicles. Fueling future space vehicles and payloads will take only minutes with the use of on-demand propellant loading systems employing autonomous umbilicals. After the vehicle is fueled, it is then ready for active departure operations requiring only a skeleton crew for support. In preparation for departure, or Go, the vehicle receives permission to enter the spaceport departure queue, much like commercial airliners do today. The vehicle initiates final system check, power-up of main propulsion, and departure from the spaceport.

The evolution of capabilities required to perform the Gas & Go functions are summarized in Figure 25. A more detailed description of the capability evolution can be found in Appendix G.

Challenges

The fueling phase of Gas & Go tends to be the limiting factor in realizing this vision. Current-day fueling operations are hazardous and necessarily time-consuming to control the hazards. Although computer systems control fueling operations, a large workforce is still required to monitor propellant loading operations. Engineers evaluate ground system performance as well as monitor for hazardous leaks that can propagate into explosive conditions. Because of the hazardous nature of these systems, maintenance poses significant challenges as well. Maintaining hazardous fueling systems requires an area of predetermined radius clear of nonessential personnel. Technicians must don protective suits when in close proximity to these systems, and they must use specialized equipment for servicing the systems. These restrictions do not allow for rapid fueling operations and impose additional support equipment maintenance on the spaceport.

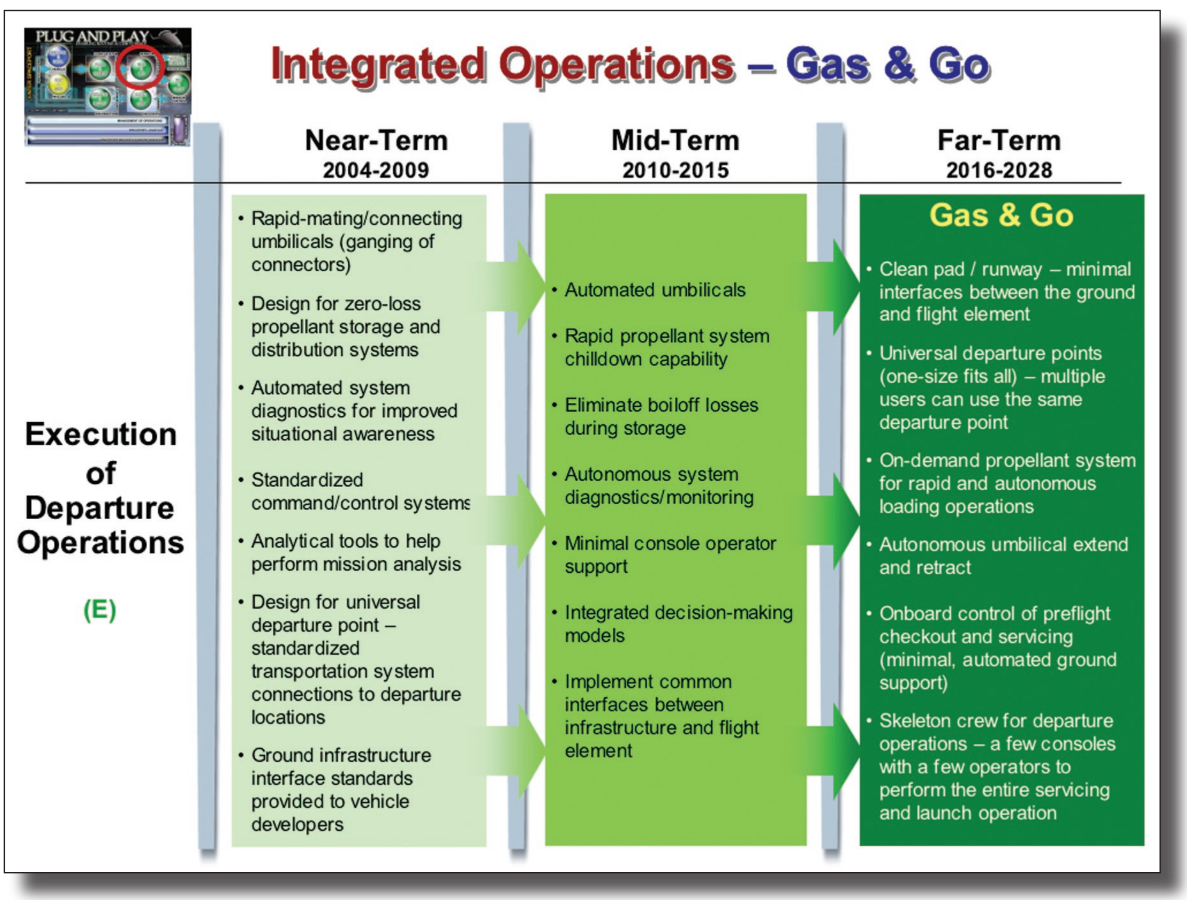


Figure 25. Gas & Go functional capabilities roadmap summary

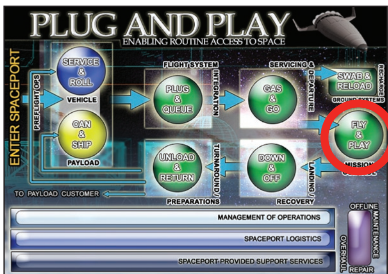
Technical Approaches

Advanced technologies can enable rapid fueling operations. Technologies required to optimize the Gas & Go phase include enhanced automation to support autonomous umbilical actions, on-demand commodity loading, and intelligent ground console operations. Standardizing interfaces between the craft and the ground systems remains an area of importance. This phase of integrated operations emphasizes minimizing hazards by using commodities with benign properties and maximizing use of automated fueling/support systems. Table 6 summarizes the key technologies associated with Gas & Go. A more detailed description of the challenges and technical approaches can be found in Appendix I.

Table 6. Key challenges and technologies for Gas & Go

Challenges	Spaceport Technologies
• Protecting workforce from exposure to hazardous operations • Reducing boiloff loss of cryogenic/ volatile propellants • Conducting last-minute and late-access operations is a hazardous • Detecting and eliminating leak sources is difficult • Transforming data into information for real-time situational awareness and decision support	• Advanced planning and scheduling tools – Dynamic scheduling – Situational awareness – Human-machine interfaces – Intelligent software agents • Low-maintenance insulation systems (e.g., for cryogenics) • Inexpensive, nonintrusive hazardous gas and leak detection systems • Self-sealing, self-cleaning cryogenic quick disconnects • Cryogenic “quick chill-and-fill” methods • Advanced decision support tools – High-volume/speed processing and display technologies – Intelligent software agents – Interoperable databases (cross-queuing, dynamic database fusion) – Human-machine interface – Artificial intelligence • Intelligent command and control systems – Situational awareness – Intelligent software agents • Integrated health management for integrated vehicle – Neural networks – Artificial intelligence – Adaptive algorithms – Data fusion techniques – Self-diagnostic/remediation techniques • Autonomous fueling systems – Leakproof connectors and seals – Low-maintenance insulation systems – Inexpensive, nonintrusive hazardous gas and leak detection systems • Commodities production and recovery and disposal management systems

4.2.5 Monitor and Manage the Flight – *Fly & Play*



Flexible and responsive flight operations control.

Key Characteristics

- **Fleet operations**
- **Separation of flight operations from mission operations**
- **Autonomous umbilical extend and retract**
- **"Free flight"**
- **On-orbit traffic coordination**

Concept of Operations

The Fly & Play phase of the generic spaceport operations model monitors and manages the flight function. Fly & Play retains the functional notion of autonomous flight as the core philosophy. This notion is founded upon current air travel concepts that use ground intervention (from the space traffic control function) to notify flight crew personnel of safety-of-flight issues and spatial coordination thereby reserving the command of the craft for the crewmembers. This concept integrates with the contemporary ideal of fleet operations.

The evolution of capabilities required to perform the Fly & Play functions are summarized in Figure 26. A more detailed description of the capability evolution can be found in Appendix G.